



TITLE:

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Transient heat transfer from a wire inserted into a vertically mounted pipe to forced flow liquid hydrogen.

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Abstract

The transient heat transfer from a Pt–Co wire heater inserted into a vertically mounted pipe, through which forced flow subcooled liquid hydrogen was passed, is measured by increasing the exponential heat input with various time periods at a pressure of 0.7 MPa and an inlet temperature of 21 K. The flow velocities range from 0.8 to 5.5 m/s. For shorter periods, the non-boiling heat transfer becomes higher than that given by the Dittus–Boelter equation due to the transient conductive heat transfer contribution. In addition, the transient critical heat flux (CHF) becomes higher than the steady-state CHF. The effect of the flow velocity and period on the transient CHF heat flux is also clarified.

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1. Introduction

Liquid hydrogen is expected as a coolant for high- T_c superconductors because its boiling point is lower than that of liquid nitrogen, and it has higher thermal conductivity, greater specific heat, and lower viscosity. With respect to its cooling design and stability during a quench, it is important to understand the transient heat transfer in a forced

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flow of liquid hydrogen as well as the steady-state one. Coeling et al. [1] measured natural convection heat transfer from a flat disk plate to saturated liquid hydrogen, which can be expressed by conventional correlations. Bewilogua et al. [2] measured the critical heat fluxes on a horizontal flat disc plate in a pool of several cryogenic liquids, including hydrogen below its critical pressure. Based on their experimental data, they determined that the best coefficient in Kutateladze's correlation was 0.16.

Tatsumoto et al. [3] developed a thermo-hydraulic experimental system for liquid hydrogen to systematically investigate pool boiling and forced convection heat transfer of liquid and supercritical hydrogen. Shiotsu et al. [4] studied transient heat transfer from a horizontal flat plate in a pool of liquid hydrogen. They reported that, unlike with liquid nitrogen, no direct transition from non-boiling to film boiling was observed. Tatsumoto et al. [5,6] measured the forced convection heat transfer of saturated liquid hydrogen in heated tubes and a heated wire in a tube, and derived a correlation with the departure from nucleate boiling (DNB) heat flux based on the experimental results.

In this study, to clarify the effect of the heating and flow rates on the transient critical heat flux (CHF), q_{cr} , we measure the transient heat transfer from a wire, inserted into a vertically mounted pipe, to a forced flow of subcooled liquid hydrogen with an exponential increase in the heat generation rate at a pressure of 0.7 MPa.

Nomenclature

C_p	specific heat of liquid ($\text{J kg}^{-1} \text{K}^{-1}$)
d	diameter of wire heater (m)
d_p	diameter of pipe (m)
D	hydraulic equivalent diameter (m)
h_c	transient conductive heat transfer length coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
k	thermal conductivity of liquid ($\text{W m}^{-1} \text{K}^{-1}$)
K_0	modified Bessel functions of the second kind of zero order
K_1	modified Bessel functions of the second kind of first order
l	length of wire heater (m)
P	pressure (MPa)
Q	heat generation (W m^{-3})
Q_0	initial heat generation (W m^{-2})
q	surface heat flux (W m^{-2})
q_{cr}	transient critical heat flux (W m^{-2})
q_{st}	steady-state critical heat flux (W m^{-2})
t	time (s)
T_{in}	inlet temperature (K)
T_{sat}	saturated temperature (K)
T_w	average surface temperature (K)
ΔT_L	excess averaged heated surface temperature beyond the inlet temperature (K)
v	velocity (Pa s)
ρ	density of liquid (kg m^{-3})
τ	period (s)

2. Experimental apparatus and method

2.1. Experimental system

Fig. 1 shows a schematic of the experimental system, that we developed earlier, and its details are presented in another paper [3]. A main cryostat is connected to a sub-tank through a hydrogen transfer line with a control valve having a Cv of 1.1. The main tank has an inner diameter of 406 mm and height of 1495 mm and is placed on a scale (Mettler Toledo WMHC 300s) that can measure up to 400 kg with a 0.002 kg resolution. The maximum inventory of liquid hydrogen is 50 L, although the total volume is 100 L. The sub-tank has an inner diameter of 310 mm and

height of 1375 mm. Several plates are installed around the top of the tanks to reduce the heat leak caused by convection and radiation. The design pressure is 2.1 MPa. A test heater, shown in Fig. 2, is immersed in the LH2 bath of the main tank and is located at one end of the transfer line. Liquid hydrogen in the main tank is pressurized to a desired value by pure hydrogen gas (99.999%) from hydrogen gas bottles controlled by a dome-loaded gas regulator. The sub-tank is maintained at atmospheric pressure by opening the release valve. Stable forced flow can be produced by adjusting the pressure difference between the tanks, and opening the control valve. The mass flow rate through the test heater is estimated by measuring the weight change of the main tank, and by measuring the flow rate of the hydrogen feed gas by using a turbine flow meter. Flow measurement error is estimated to be within 0.1 g/s for a 40 s measurement period [3]. The liquid hydrogen level in the main tank can also be determined by measuring its weight change. The inlet liquid temperature of the pipe and bath temperature are measured using a Cernox sensor with an accuracy of 10 mK. Four power leads are installed to introduce a heating current to the test heater of up to 500 A. One of the leads is a common neutral line. For protection against explosion, the power cables are covered with nitrogen gas blanket pipes that maintain nitrogen pressure at 105 kPa, which is slightly higher than atmospheric pressure.

2.2. Test heater

A wire heater inserted into a vertically mounted pipe is shown in Fig. 2 and its details are presented in another paper [6]. The wire heater, made of Pt-Co alloy, has a diameter of 1.2 mm and heated length of 120 mm. The wire heater is located on the central axis of the pipe, which has a diameter of 8 mm and length of 210 mm, and is made of fiber-reinforced plastic (FRP) for thermal and electrical insulation. The entrance lengths of the pipe heaters are more than 10 times longer than the hydraulic equivalent diameter because the flow velocities correspond to a Reynolds number, Re , higher than 1.0×10^4 in this study.

2.3. Experimental procedure

Details are presented in another paper [5, 6]. The exponential heat generation of $Q = Q_0 \exp(t/\tau)$, where τ is the period, is applied to the Pt-Co wire heater using a fast-response direct-current source (24 V, 400 A max.), which is controlled by a digital computer to provide the desired time function for the heat input. The average temperature of the heater is obtained from its electric resistance, which has been measured using a double-bridge circuit in saturated liquid hydrogen and nitrogen. The double-bridge circuit is first balanced at bath temperature. The output voltage

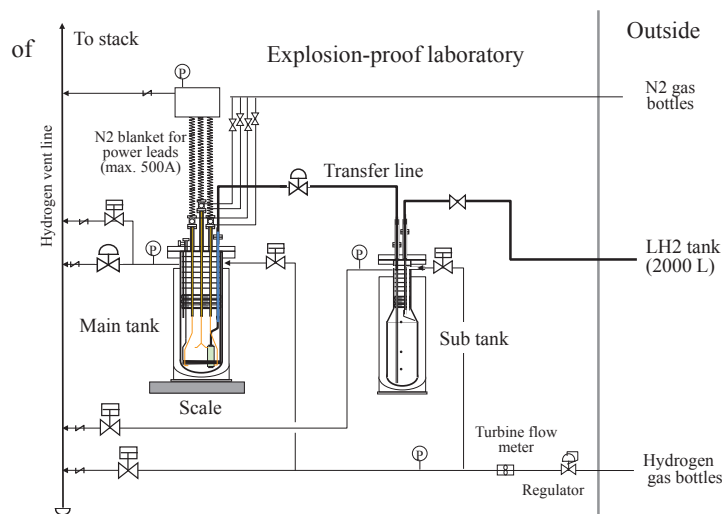


Fig.1. Experimental apparatus.

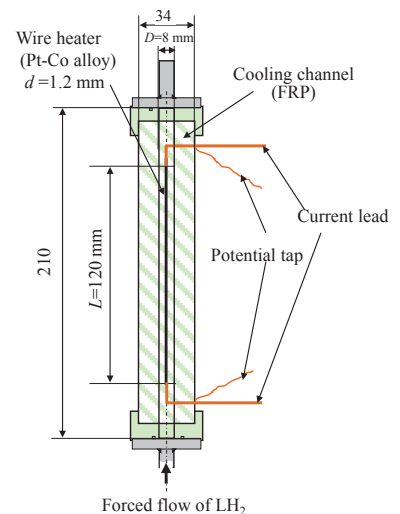


Fig. 2. Test heater.

of the bridge circuit caused by the heater resistance deviation in the current heating, the voltage drop across the potential taps of the heater, and the voltage drop across the standard resistance are all amplified and simultaneously sampled at a constant time interval. The average temperature is estimated using the temperature dependence of the electrical resistance, which was calibrated previously in a range from 20 K to the ambient temperature. The heat generation rate is calculated from the measured voltage drops through the heater and the standard resistance. The surface heat flux, q , is the difference between the heat generation rate and time rate of change of the energy stored in the heater. The average surface temperature of the heater, T_w , is calculated from the average temperature and the surface heat flux by solving a conduction equation in the wire's radius direction. The double-bridge circuit measuring the heater resistance has an accuracy of 1×10^{-4} . A temperature deviation of about 0.1 K can be measured by the bridge. The bath temperature and inlet temperature are measured by Cernox sensors with an accuracy of 10 mK. Only the temperature increment of the heater from the inlet temperature is necessary to perform the analysis. Accordingly, experimental error is estimated to be within 0.1 K of the heater surface temperature and within 2% of value of the heat flux.

We measured the transient heat transfer from the wire, located on the center axis of the vertically mounted tube, to the forced flow of the subcooled liquid hydrogen at a pressure of 0.7 and an inlet temperature of 20.9 K, by exponentially increasing the heat input, $Q_0 \exp(t/\tau)$. The exponential period of the heat input was changed from 10.0 s to 19 ms.

3. Results and discussion

3.1. Transient heat transfer characteristics in a forced flow of subcooled liquid hydrogen

Fig.3 shows the transient heat transfer characteristics of a wire located at the central axis of a pipe containing a forced flow of subcooled liquid hydrogen at a pressure of 0.7 MPa and an inlet temperature of 21 K. These characteristics correspond to a subcooling temperature of 8.23 K for the velocities of (a) 0.8 m/s and (b) 5.5 m/s. The transverse axis indicates the excess averaged heated surface temperature beyond the inlet temperature $\Delta T_L (=T_w - T_{in})$. For relatively slow heating, the heat flux increases along a curve predicted by the Dittus–Boelter equation [7] up to the onset of nucleate boiling, which appears at T_w slightly higher than the T_{sat} value. With relatively little increase in ΔT_L , the heat flux steeply increases up to a certain upper limit heat flux for the nucleate boiling, called the CHF, when the heat transfer characteristic changes to that in a film boiling regime. With a decrease in τ , the non-boiling heat transfer becomes higher than that predicted by the Dittus–Boelter equation due to the transient conductive heat transfer contribution, which appears for shorter τ values with increase in flow velocity. The transient nucleate boiling heat transfer is almost unaffected by the period of exponential heating. The transient CHF's become higher for shorter τ values.

Fig. 4 shows the effect of τ on the non-boiling heat transfer coefficient. The approximate transient conductive heat transfer coefficient, h_c , with exponential heat generation, $Q_0 \exp(t/\tau)$, is given as follows [8]:

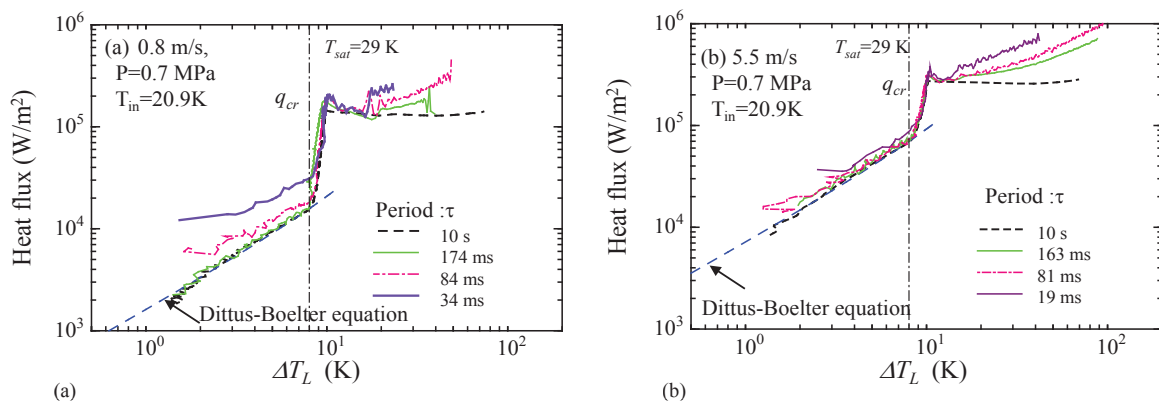


Fig. 3. Transient forced convection heat transfer at 0.7 MPa under subcooled condition. (a) $v=0.8$ m/s; (b) $v=5.5$ m/s.

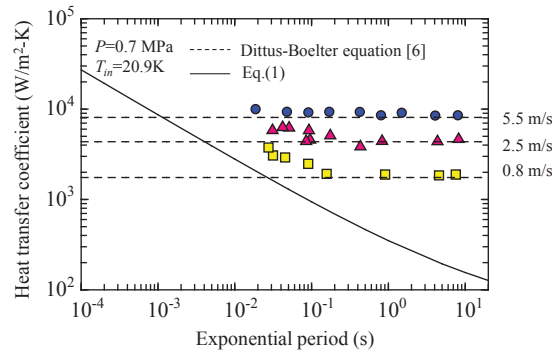


Fig. 4. Effect of the period τ on the non-boiling heat transfer coefficient.

$$h_c = \left(\frac{k\rho C_p}{\tau} \right)^{0.5} \frac{K_1(\mu d/2)}{K_2(\mu d/2)}, \quad (1)$$

$$\mu = \left(\frac{\rho C_p}{k\tau} \right)^{0.5}, \quad (2)$$

where k is the thermal conductivity, ρ is the density and C_p is the specific heat. The subscript l indicates a liquid. K_1 and K_0 are the modified Bessel functions of the second kind of zero and first orders. For long τ values, the non-boiling heat transfer coefficients agree with those for steady-state, which are predicted by the Dittus-Boelter equation. For shorter τ values, they appear to become higher and approach the curve by Eq. (1). For higher flow velocities, the steady-state values become larger and a transient conductive heat transfer contribution appears with shorter τ values.

3.2. Transient DNB heat flux in forced flow

Fig. 5 shows the transient CHF, q_{cr} , by the exponential heating with τ values ranging from 19 ms to 10 s at a pressure of 0.7 MPa and an inlet temperature of 21 K. For a flow velocity of 0.8 m/s, the transient CHF's almost agree with steady-state CHF, q_{st} , for $\tau > 0.92$ s. For $\tau < 0.92$ s, the CHF's become greater than q_{st} . For $v = 2.5$ m/s and $v = 5.5$ m/s, transient CHF's become higher than q_{st} for $\tau < 2$ s and $\tau < 5$ s, respectively. At higher flow velocities, the CHF enhancement caused by exponential heating occurs for longer τ values. It seems that the increasing rates of q_{cr} from q_{st} are independent of flow velocity.

Fig. 6 shows the effect of τ on $q_{cr} - q_{st}$ with v as a parameter. We found that the measured values of $q_{cr} - q_{st}$ follow a power law of $\tau^{-0.5}$, independent of v . However, q_{cr} for longer τ values agrees with q_{st} , which depends on v as shown in Fig. 5.

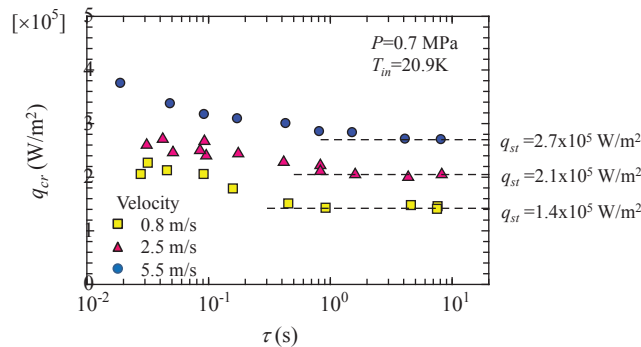


Fig. 5. Transient CHF q_{cr} by the exponential heating with the period τ .

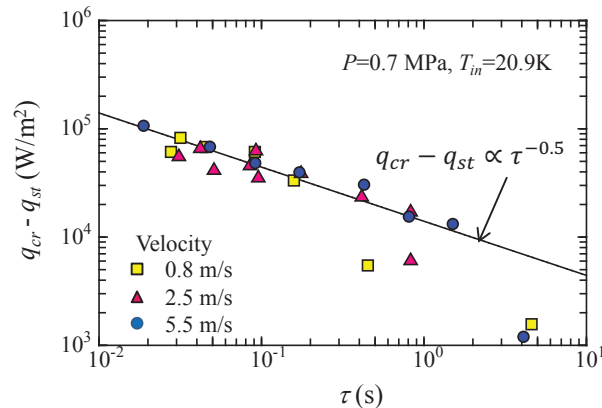


Fig. 6. Effect of τ on the increase in q_{cr} from q_{st} .

4. Conclusion

We measured the transient heat transfer from a wire inserted into a vertically mounted pipe to a forced flow of subcooled liquid hydrogen by increasing the exponential heat inputs at various flow rates at a pressure of 0.7 MPa and an inlet temperature of 21 K, which corresponds to the subcooling of 8 K. Experimental results lead to the following conclusions:

For relatively slow heating ($\tau > 1$ s), the non-boiling heat transfer agrees with that of the steady-state, which is predicted by the Dittus–Boelter equation. For faster exponential heating (shorter τ values), it becomes higher due to the transient conductive heat transfer contribution. For higher flow velocities, it also becomes higher, and the transient conductive heat transfer contribution appears for shorter τ values.

The transient nucleate boiling heat transfer is almost unaffected by τ . The transient CHF becomes larger than q_{st} for shorter τ values. For higher flow velocities, the CHF enhancement caused by exponential heating appears for longer τ values. We found that the increase in the transient CHF from the steady-state CHF is expressed by the same curve with $\tau^{-0.5}$, independent of the flow velocity.

Acknowledgements

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